Full length article

Energy-per-bit performance analysis of relay-based visible-light communication systems

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A B S T R A C T

Relaying systems, such as amplify-and-forward (AF), decode-and-forward (DF), selective DF (SDF) and incremental DF (IDF) relaying are usually used to ensure high performance and reliability for communication systems. A comprehensive energy efficiency performance study for different half-duplex relaying protocols, namely DF, SDF and IDF over visible light communication (VLC) channels is provided in this paper. Accurate analytical expressions for both outage probability and the minimum energy-per-bit performance of the aforementioned relaying systems are derived. For the sake of comparison and to justify the use of relays in the proposed system, the performance of a single-hop scenario is analyzed and compared to the relay-based links. The accuracy of the analysis is verified by Monte Carlo simulations. The results reveal that the single-hop VLC system offers the poorest performance compared to that offered by VLC relay-based systems particularly for relatively high end-to-end distances. However, the best performance is offered by SDF and IDF schemes as they have a lower outage probability than other systems under consideration. This work also shows that the performance of the systems under consideration is affected by some parameters, such as the vertical distance to user plane and the maximum cell radius of the LED.

1. Introduction

The visible light communication system (VLC) is, at present, one of the new and emerging technologies in optical wireless communication technologies (OWC) which is predicted to play a very important role in indoor applications. This technology uses light emitting diodes (LEDs) to transmit data to the end users, this makes its potential implementation complexity and cost very low. Thanks to these reasons, VLC has become a very attractive technology and one of the most crucial green communication technologies for such applications [1]. Recent works have considered VLC as an alternative or complementary technology to communications [2–4]. However, as other communication techniques, the VLC technology has its limitations, such as interference caused by the overlapping of adjacent LED light fixtures and the instability of signal reception due to the small area covered by each LED, leading to frequent switching [5,6]. For greater reliability and coverage, ceiling lights and the other light sources, such as desk or floor lights in indoor environments can be deployed as relays.

The use of relays with VLC systems is not only for improving the capacity but also to ensure the transmission when the end user is shadowed or blocked from the source node. Different relaying protocols can easily be implemented with VLC systems, such as amplify-and-forward (AF) and decode-and-forward (DF) [6–8]. Deployment of AF relays in hybrid power line (PLC)/ VLC communication was investigated in [6]. The results indicated that the performance of the system improves as the relay gain increases, which justifies the implementation of the relay in the system. DF relaying protocol implementation in which a cooperative free space optical (FSO)-VLC communication system was studied in [9]. The information source sent data through the FSO link, which acted as the backbone of the VLC system, and the DF relay was located in-between the two links. It was reported that this system was efficient in terms of capacity. Improving the performance of the VLC systems by developing cooperation between light sources in indoor environment was investigated in [10]. The authors concluded that the achievable performance by deploying DF relaying was slightly higher than that accomplished by the implementation of AF relaying. Recent studies have investigated the implementation of other relay protocols in communication systems include incremental DF and selective DF relaying, see e.g., [11–13]. It was found that a considerable performance improvement can be achieved with the deployment of these types of relays. It is also shown that the reliability of the communication systems can be enhanced by increasing the number of relays on the network. Although greater performance is achieved by increasing the number of relays in the system, the total power consumption becomes a crucial issue. This is because of the increase in static power (i.e., the power consumption associated with the circuitry) [13].

Previous studies have primarily concentrated on energy efficiency in relay-based communication systems [14–17]. The authors in [14,15] investigated different techniques to enhance the energy efficiency in relaying PLC systems. While the former proposed a certain technique to reduce the transmit power in the PLC relay-assisted system which can be achieved by optimizing some of the system parameters such as transmit power. The latter considered harvesting the energy of the undesired impulsive noise at the AF relay in order to reduce the total energy consumption. The study in [16,18] considered a hybrid VLC/RF relay-based communication system to overcome the issue of VLC systems coverage. The authors studied the relays ability to harvest the energy from the first phase (i.e., VLC link) and use it as transmission power for the second phase (i.e., RF link). A cooperative VLC/RF communication system in the presence of DF relays operating with energy harvesting (EH) technique was investigated in [17]. It was concluded that the performance of such a system can be improved using DF relaying system between the VLC and RF links where the energy from the first hop is harvested and used to supply the relay with additional resources. In [19] the authors studied the possibility of achieving improved energy efficiency and increasing the achievable data rate by integrating VLC and RF links and the results were promising. A solar panel receiver optical wireless communication was proposed in [20] where the receiver can harvest the modulated light by converting it into an electrical signal and using it for communication purposes. Both studies in [21,22] proposed an optimal EH time switching protocol design where the relay harvests energy from the received information signal and then the harvested energy is used to forward the signal to the end users.

Although a large and growing body of literature has investigated this topic, the authors of this paper believe that a comprehensive and in-depth theoretical outage probability and energy analysis of relaying VLC systems is still missing in the previous work. Therefore, the objective of the present paper is to investigate the outage probability and energy efficiency of different relaying protocols, namely DF, SDF and IDF, over VLC channels. The performance of a single-hop VLC system is also analyzed in this paper. Furthermore, for the sake of comparison and to highlight the achievable gains of each relaying protocol, performance comparisons between the different system configurations is carried out in this paper in terms of outage probability and energy efficiency. The derivation of the accurate analytical expressions for the outage probability and energy efficiency of the different system scenarios represents the main contribution of this paper. The derivation of these expressions offers the opportunities to have better understanding on the behavior of the different systems under consideration in this work which is essential for proper VLC systems designing. The theoretical results of the derived expressions are validated by computer simulations throughout the paper. The results of this work indicated that the superiority of IDF and SDF relay-assisted VLC systems over the non-cooperative DF-based relaying scheme and single-hop systems .

The rest of the paper is organized as follows. The system model is presented in Section 2. Section 3 presents the system performance analysis. Discussions of the numerical results are presented in Section 4. Finally, the conclusions of this paper are drawn in Section 5.

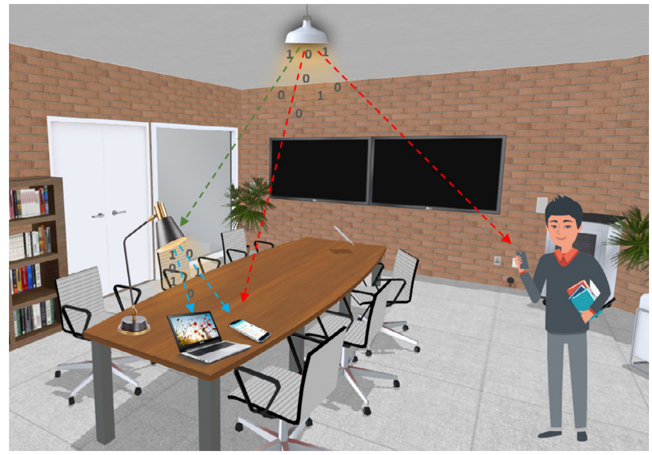

Fig. 1. System model for the cooperative VLC system.

2. System model

This section presents the proposed system model for the cooperative VLC system where an intermediate light source acts as a half-duplex relay terminal. The system model under consideration is shown in Fig. 1. It consists of a source node (S), a relaying node (R) and a destination nod (D). The complex channel gains h_1, h_2 and h_3 represent the source-to-relay, the relay-to-destination and source-to-destination channel gains, respectively. All channels are assumed to be independent and identically distributed. In this paper, we only take in consideration the line-of-sight (LOS) component of the down-link transmission of the LED which represents almost 90% of the total received signal [23].The coverage area of the LoS of LED is a circle as it can be seen from Fig. 2. The LED (the source modem) is located on the ceiling with vertical distances L_{SR} and L_{SD} to the intermediate light source (the relay modem) and destination planes, respectively. The euclidean distance from the source to the relay is d_1 and d_3 represents the source-to-destination euclidean distance. The vertical distance from the relay modem to the user plane is L_{RD} and euclidean distance to destination is d_2. A VLC channel environment is shown in Fig. 2. The VLC channel is subjected to a random distribution which is affected by the uniform distribution of the user's location [23]. It is worth mentioning, for simplicity and without loss of generality, that noise over the links is assumed to be additive white Gaussian noise (AWGN).

3. Performance analysis

In this section, the authors analyze and investigate the outage probability and energy efficiency performance of the transmission protocols mentioned previously.

3.1. Single-hop VLC system

The single-hop approach is a one phase system where the communication occurs directly between the source and the end user. In such cases, the energy/bit performance can be determine by

$$E_{SH} = \frac{P_{SH}}{R_b}, \tag{1}$$

where E_{SH} represents the energy per bit of the one phase communication, P_{SH} is the optimal source power for a known outage probability for the single-hop scheme. This is also referred to a minimum transmit power needed to achieve a given value of

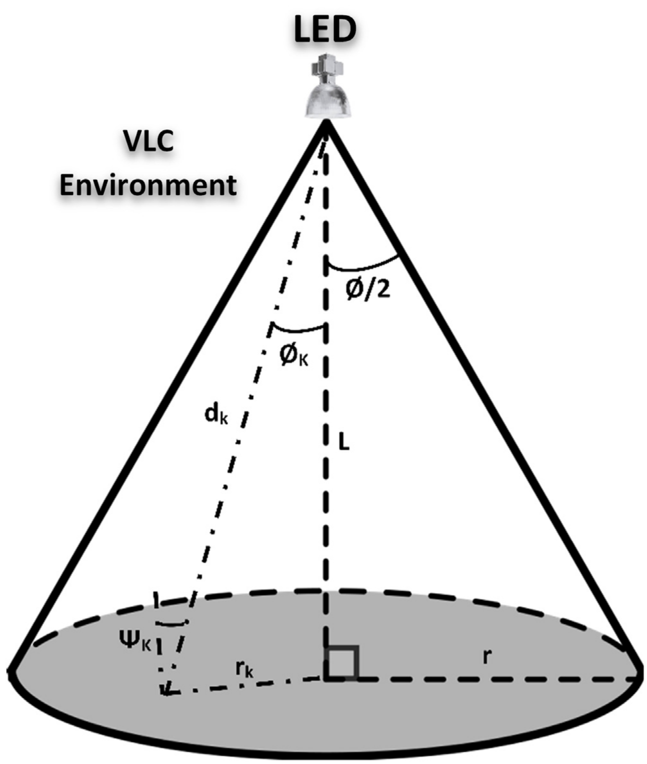

Fig. 2. A LOS channel model for the proposed VLC environment.

outage probability. Here, R_b is the data rate calculated in bits/s and equal to the spectral efficiency of the system (ε) multiplied by the bandwidth of the system (B).

Now we derive the average outage probability for the single-hop VLC system, which is simply can be defined as the probability that the instantaneous capacity of a communication system is less than a required threshold. To start with, the received signal at the destination can be given by

$$y_d\,(t) = \sqrt{P_{SH}}h_3 s(t) + n_d, \tag{2}$$

where P_{SH} denotes the source transmit power, $s(t)$ is the information signal with $\mathrm{E}[s] = 1$, n_d is the noise at the destination which is assumed to be complex Gaussian with zero mean and variance σ_r^2.

The signal-to-noise ratio SNR at the destination can be written as follows

$$\gamma_d = \frac{P_{SH}\,|h_3|^2}{\sigma_d^2}. \tag{3}$$

In such channel, the end-to-end outage probability, which is simply defined as the probability that the instantaneous SNR of the system is less than a certain threshold value, ε, can be found as follows

$$P_{outage}^{SH} = Pr\left\{\log_2\left(1 + \gamma_d\right) < \varepsilon\right\}. \tag{4}$$

which mathematically can be manipulated and written as

$$P_{outage}^{SH} = Pr\left\{\gamma_d < \left(2^{\varepsilon} - 1\right)\right\}. \tag{5}$$

It is obvious the expression in (5) represents the cumulative distribution function (CDF) of the SNR at the destination. Hence, we can express (5) as

$$P_{outage}^{SH} = F_{\gamma_d}(2^{\varepsilon} - 1), \tag{6}$$

where $F_{\gamma_d}(\cdot)$ represents the CDF of γ_d.

As previously mentioned that the VLC channel is subjected to a random distribution which is affected by the uniform distribution of the user's location and considering the Lambertian radiation pattern for LED light emission [9], the VLC channel gain can be given by

$$h_{VLC} = \frac{m_k + 1}{2\pi d_k^2} A_d \cos^{m_k}(\phi) \cos\left(\Psi_K\right) U\left(\Psi_K\right) g\left(\Psi_K\right) R_p, \tag{7}$$

where A_d denotes the detection area of the detector, $U\left(\Psi_K\right)$ represents the optical filter gain, $g\left(\Psi_K\right)$ is the optical concentration gain, R_p represents the photo-detector responsivity, ϕ is the total angle of the LED, $\cos^{m_k}(\phi) = \cos\left(\Psi_K\right) = \frac{L}{\sqrt{r_k^2 + L^2}}$, L is the vertical distances from the LED to the user plane, d_k is the source-to-destination euclidean distance which is equal to $\sqrt{r_k^2 + L^2}$ and m_k is the order of the Lambertian radiation pattern which is given by

$$m_k = \frac{-1}{\log_2(\cos(\phi/2))}, \tag{8}$$

where the semi-angle of the LED represented by $\phi/2$.

The location of the user is assumed to be uniformly distributed in a circle with maximum cell radius r and the PDF is given as

$$f_{r_k}(r) = \frac{2r_k}{r^2}. \tag{9}$$

By using the following equation which is the change-of-variable method used in [6] we can drive the PDF of the VLC channel gain.

$$f_{h_k}(h) = \left| \frac{\partial}{\partial h} u^{-1}(h) \right| f_{r_k}(u^{-1}(h)). \tag{10}$$

Where you u^{-1} is the inverse function of the h_{VLC}. Hence, the PDF of the VLC channel gain can be written as

$$f_{h_k(t)} = \frac{2Q^{\frac{2}{2+m}} \left((m_k + 1)\, L^{m_k+1}\right)^{\frac{2}{m+3}} t^{-\frac{1}{m_k+3}-1}}{(m_k + 3)r^2}, \tag{11}$$

where r denotes the maximum cell radius of the LoS,

$$Q = \frac{1}{2\pi} A_d U\left(\Psi_K\right) g\left(\Psi_K\right) R_p. \tag{12}$$

where $t \in [C_{min}, C_{max}]$, where $C_{min} = \frac{\left(Q(m_k+1)L^{m_k+1}\right)^2}{(r^2+L^2)^{m_k+3}}$ and $C_{max} = \frac{\left(Q(m_k+1)L^{m_k+1}\right)^2}{L^{2(m_k+3)}}$. By using (11), the PDF of the instantaneous SNR can be obtained as

$$f_{h_k^2}(t) = \frac{-Q^{\frac{2}{2+m_k}} \left(\beta L^{\beta}\right)^{\frac{2}{\alpha}} t^{-\frac{m_k+5}{\alpha}}}{\beta r^2}, \tag{13}$$

where $\alpha = m_k + 3$ and $\beta = m_k + 1$.

By integrating (13) over $[C_{min}, h]$ we can calculate the CDF of the VLC link which represents the outage probability of the system as

$$P_{outage}^{VLC} = \frac{-1}{r^2}\left(\beta Q L^{\beta}\right)^{\frac{2}{\alpha}} h^{-\frac{1}{\alpha}} + \left(1 + \frac{L^2}{r^2}\right). \tag{14}$$

Now using (14) we can define the average outage probability of the considered single-hop VLC system as follows

$$P_{outage}^{SH} = \frac{-1}{r^2}\left(\beta Q L_{SH}^{m_k+1}\right)^{\frac{2}{\alpha}} \left(|h_3|^2\right)^{-\frac{1}{\alpha}} + \left(1 + \frac{L_{SH}^2}{r^2}\right). \tag{15}$$

By using (3) and (6) we obtain the following

$$P_{outage}^{SH} = \frac{-1}{r^2}\left(\beta Q L_{SH}^{\beta}\right)^{\frac{2}{\alpha}} \left(\frac{\left(2^{\varepsilon} - 1\right)\sigma_d^2}{P_{SH}}\right)^{\frac{-1}{\alpha}} + \left(1 + \frac{L_{SH}^2}{r^2}\right). \tag{16}$$

By using basic mathematical manipulations we easily express the optimal transmit power that can achieve the given outage probability as follows

$$P_{SH}=\left(\frac{\left((2^{\varepsilon}-1)\,\sigma_d^2\right)^{\frac{-1}{\alpha}}\left(\beta QL_{SH}^{\beta}\right)^{\frac{2}{\alpha}}}{-r^2P_{outage}^{SH}+r^2+L_{SH}^2}\right)^{-\alpha}. \tag{17}$$

Finally, we can obtain the energy-per-bit performance of the system under consideration by substituting (17) into (1) which can be given by

$$E_{SH}=\frac{1}{R_b}\left(\frac{\left((2^{\varepsilon}-1)\,\sigma_d^2\right)^{\frac{-1}{\alpha}}\left(\beta QL_{SH}^{\alpha}\right)^{\frac{2}{\alpha}}}{-r^2P_{outage}^{SH}+r^2+L_{SH}^2}\right)^{-\alpha}. \tag{18}$$

3.2. Decode-and-forward relaying VLC system

This a non-cooperative relaying scheme where the destination only communicate with DF relay which receives the information signals from the source and then this data is decoded and forwarded to its destination. In such cases, in accordance to [13] one can calculate the total energy-per-bit consumption as follows

$$E_{DF}=\frac{P_{DF}}{R_b}\left(P_{outage}^{SR}+2\left(1-P_{outage}^{SR}\right)\right), \tag{19}$$

where E_{DF} denotes the total energy-per-bit consumption, P_{DF} is the minimum transmit power which required to achieve a certain outage probability of the entire system and P_{outage}^{SR} represents the outage probability of the source-to-relay channel.

To began with, we derive the end-to-end outage probability of the DF-assisted VLC system in order to obtain the energy efficiency of this system. Assuming that the source-to-relay distance and the relay-to-destination distance are equal, the overall outage probability of entire system can be written as

$$P_{outage}^{DF}=P_{outage}^{SR}+\left(1-P_{outage}^{SR}\right)P_{outage}^{RD}, \tag{20}$$

where P_{outage}^{RD} represents the outage probability of the second phase of the communication (i.e., relay-to-destination link).

Now, considering the assumption of that the relay is placed halfway between the source and the end-user and assuming that both source and relay have same transmit power and then following the same steps that were taken in 3.1, P_{outage}^{SD} and P_{outage}^{RD} can be written as

$$P_{outage}^{SR}=\frac{-1}{r^2}\left(\beta QL_{SR}^{\beta}\right)^{\frac{2}{\alpha}}\left(\frac{(2^{\varepsilon}-1)\,\sigma_r^2}{P_{SR}}\right)^{\frac{-1}{\alpha}}+\left(1+\frac{L_{SR}^2}{r^2}\right), \tag{21}$$

$$P_{outage}^{RD}=\frac{-1}{r^2}\left(\beta QL_{RD}^{\beta}\right)^{\frac{2}{\alpha}}\left(\frac{(2^{\varepsilon}-1)\,\sigma_d^2}{P_{RD}}\right)^{\frac{-1}{\alpha}}+\left(1+\frac{L_{RD}^2}{r^2}\right), \tag{22}$$

where σ_r^2 is the noise variance at the relay which assumed to be equal to that at the destination. When both links of the proposed VLC system are identical, which means that both links have the same average outage probability value (i.e., $P_{outage}^{SR}=P_{outage}^{RD}$), then the end-to-end average probability can be expressed as

$$P_{outage}^{DF}=P_{outage}^{*}\left(2-\left(P_{outage}^{*}\right)\right), \tag{23}$$

where $P_{outage}^{*}=P_{outage}^{SR}=P_{outage}^{RD}$. Considering the assumption of the previous step and substituting (21) and (22) into (23) we obtain (24).

$$P_{outage}^{DF}=\left(\frac{-1}{r^2}\left(zQL_{DF}^{z}\right)^{\frac{2}{\alpha}}\left(\frac{(2^{\varepsilon}-1)\,\sigma_{DF}^2}{P_{DF}}\right)^{\frac{-1}{\alpha}}+\left(1+\frac{L_{DF}^2}{r^2}\right)\right),$$
$$\left(2-\left(\frac{-1}{r^2}\left(zQL_{DF}^{z}\right)^{\frac{2}{\alpha}}\left(\frac{(2^{\varepsilon}-1)\,\sigma_{DF}^2}{P_{DF}}\right)^{\frac{-1}{\alpha}}+\left(1+\frac{L_{DF}^2}{r^2}\right)\right)\right) \tag{24}$$

where $P_{DF}=P_{SR}=P_{Rd}$, $L_{DF}=L_{SR}=L_{RD}$ and $\sigma_{DF}^2=\sigma_r^2=\sigma_d^2$.

Now, using some basic algebraic manipulations we can obtain a close form for the minimum transmit power, which is required to accomplish a certain outage probability, and it can be expressed as

$$P_{DF}=(2^{\varepsilon}-1)\,\sigma_d^2\left(\frac{\left(1-\left(1-P_{outage}^{DF}\right)^{0.5}\right)-\left(1+\frac{L_{DF}^2}{r^2}\right)}{\frac{-1}{r^2}\left(zQL_{DF}^{z}\right)^{\frac{2}{\alpha}}}\right)^{\alpha}. \tag{25}$$

Finally, we substitute (25) into (19) to find the energy/bit performance of the DF-based VLC system which can be written as in (26)

$$E_{DF}=\frac{1}{R_b}\left((2^{\varepsilon}-1)\,\sigma_d^2\left(\frac{\left(1-\left(1-P_{outage}^{DF}\right)^{0.5}\right)-\left(1+\frac{L_{DF}^2}{r^2}\right)}{\frac{-1}{r^2}\left(zQL_{DF}^{z}\right)^{\frac{2}{\alpha}}}\right)^{\alpha}\right)$$
$$\left(P_{outage}^{SR}+2\left(1-P_{outage}^{SR}\right)\right) \tag{26}$$

3.3. Selective DF relaying VLC system

There are two time slot in the selective DF cooperative strategy, where the relay and the destination receive the information signal sent by the source in the first slot, the end-user will receive the decoded signal sent by the relay in the second time slot. The destination in such cooperative relaying strategy combines the two copies of the signals that received from the source and the relay nodes, which is called spatial diversity, which is in terms substantially improves the reliability of the proposed SDF-based system [24]. Unlike the IDF relaying approach which will be discussed in 3.4, the relay in SDF strategy will always cooperate as long as its received signal is successfully decoded. In such cases, in accordance to [13] the overall energy-per-bit consumption can be calculated as

$$E_{SDF}=P_{outage}^{SR}\frac{P_{SDF}}{R_b}+\left(1-P_{outage}^{SR}\right)\frac{2P_{SDF}}{R_b}, \tag{27}$$

where E_{SDF} is the consumed energy-per-bit for the SDF-based VLC system and P_{SDF} represents the minimum transmit power that is required to achieve a given outage probability for the proposed system. First of all we derive the outage probability of the system under consideration in order to calculate the energy/bit for this system, which can be written as

$$P_{outage}^{SDF}=P_{outage}^{SH}\left(P_{outage}^{SR}+\left(1-P_{outage}^{SR}\right)P_{outage}^{RD}\right), \tag{28}$$

By keeping in mind that both source-to-relay and relay-to-destination links are identical and the transmit power of the source and relay nodes are equal, the end-to-end outage probability of the proposed SDF system can be simplified to

$$P_{outage}^{SDF}=P_{outage}^{SH}\left(P_{outage}^{*}\left(2-P_{outage}^{*}\right)\right), \tag{29}$$

where $P_{outage}^{*}=P_{outage}^{SR}=P_{outage}^{RD}$.

Substituting (16), (21) and (22) into (29) we obtain (30).

$$P_{outage}^{SDF} = \left(\frac{-1}{r^2} \left(zQL_{SH}^z\right)^{\frac{2}{\alpha}} \left(\frac{(2^{\varepsilon}-1)\,\sigma_{SDF}^2}{P_{SDF}} \right)^{\frac{-1}{\alpha}} + \left(1+\frac{L_{SH}^2}{r^2}\right) \right) \left(\frac{-1}{r^2} \left(zQL_{SDF}^z\right)^{\frac{2}{\alpha}} \left(\frac{(2^{\varepsilon}-1)\,\sigma_{SDF}^2}{P_{SDF}} \right)^{\frac{-1}{\alpha}} + \left(1+\frac{L_{SDF}^2}{r^2}\right) \right) \left(2 - \left(\frac{-1}{r^2} \left(zQL_{SDF}^z\right)^{\frac{2}{\alpha}} \left(\frac{(2^{\varepsilon}-1)\,\sigma_{SDF}^2}{P_{SDF}} \right)^{\frac{-1}{\alpha}} + \left(1+\frac{L_{SDF}^2}{r^2}\right) \right) \right) \tag{30}$$

3.4. Incremental DF relaying VLC system

Basically, IDF relay will only decode-and-forward the data if direct communication between the source and destination is missing, in another word, the source fails to send data through the direct link. Furthermore, the required data rate should be achieved by the first link (i.e., source-to-relay link). This means that the IDF will not take place as long as the direct-links is able to achieve the required link quality which leads to less power consumption and better energy efficiency [25]. Considering this, the energy consumption of the system can be written as

$$E_{IDF} = \left(1 - P_{outage}^{SD}\right) \frac{P_{IDF}}{R_b} + P_{outage}^{SD} P_{outage}^{SR} \frac{P_{IDF}}{R_b} + P_{outage}^{SD} \left(1 - P_{outage}^{SR}\right) \frac{2P_{IDF}}{R_b}, \tag{31}$$

where E_{IDF} is the consumed energy-per-bit for the IDF system and P_{IDF} is the minimum transmit power for a given outage probability of the considered system. Each term in (31) represents a different scenario, where the first term refers to the energy consumption when the source signal is correctly decoded by destination node, the second term represents energy consumed when both relay and destination modems cannot correctly decode the information signal sent by the source and third term indicates the energy consumption when the IDF relay cooperates.

For the sake of brevity, the average outage probability of the IDF-assisted VLC system can be obtained from (30) as it is equal to that of the SDF-based VLC system discussed in the previous subsection. However, the energy-per-bit for this scheme derived following the same procedure that was used to calculate that of the SDF relaying VLC system in 3.4.

4. Numerical results

This section presents and discusses some numerical results of the derived expressions for both the average outage probability and energy efficiency of the systems under consideration. Monte Carlo simulations are provided to validate the numerical results. The system parameters under consideration are, unless specified otherwise, as follows: the transmit power of the source and relay nodes is 0.33 W, input SNR is 10 dB, $A_d = 0.0001$ m^2, $U(\Psi_K) = 0$ dB, $g(\Psi_K) = 5$ dB, $R_p = 1$ A/W, $r = 3.6$ m, $L_{SH} = 4$ m, $L_{SR} = L_{RD} = 2$ m and $\phi/2 = 60°$ [6].

4.1. Average outage probability

In this subsection, different system scenarios and parameters are considered to discuss the outage probability performance of the proposed systems. It is clear from Figs. 3–5 that the analytical results of the Eqs. (16), (24) and (30), and simulation results are in perfect agreement which supports the accuracy of our theoretical analysis. The discussion of the results begin with Fig. 3 which presents some numerical results of the average outage probability plotted versus different values of the threshold. It is apparent from this figure the both the SDF and IDF relaying

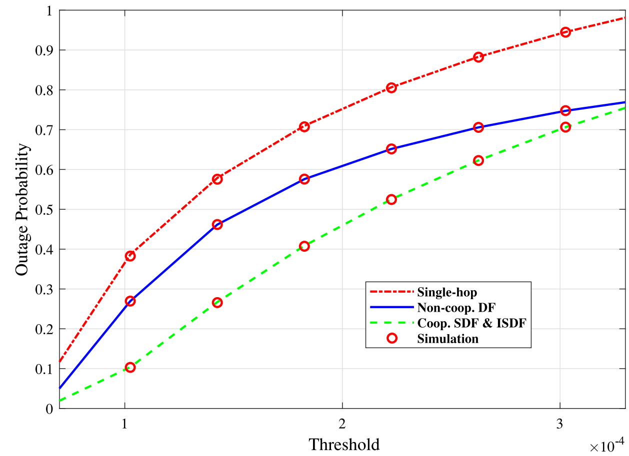

Fig. 3. Average outage probability performance with respect to threshold.

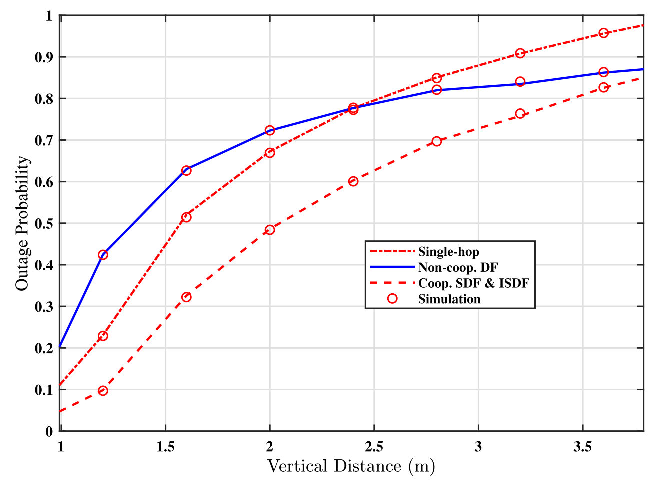

Fig. 4. Average outage probability performance versus the vertical distance to the user plane.

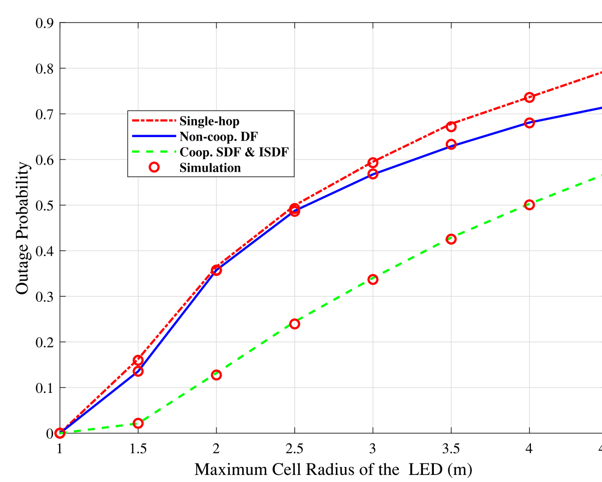

Fig. 5. Average outage probability performance versus the maximum cell radius of the LED.

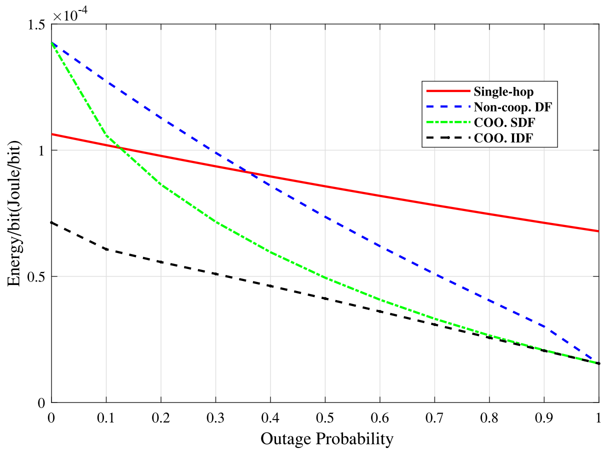

Fig. 6. Energy-per-bit performance as a function of outage probability.

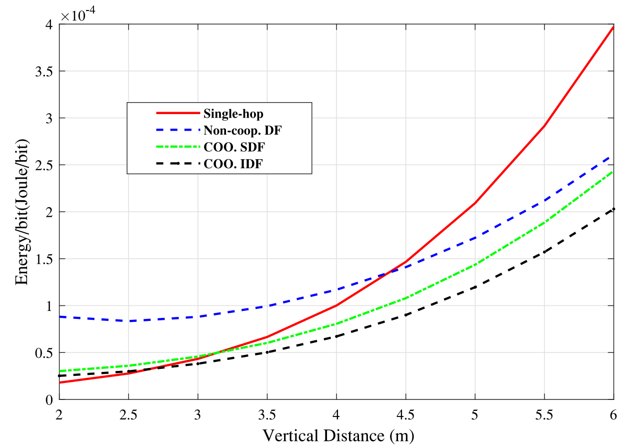

Fig. 7. Energy-per-bit performance versus vertical distance to the user plane.

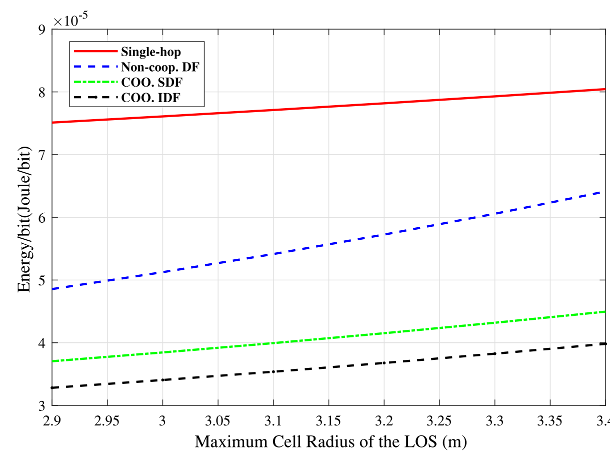

Fig. 8. Energy consumption with respect to the maximum cell radius of the LED.

protocols have the superior performance over the other system setups. The other obvious observation in this figure is that the DF-assisted systems have better performance than that provided by single-hope system.

In order to investigate the effect of the vertical distance between the source or the relay and the user plane on the performance of the proposed systems, the average outage probability is plotted with respect to the vertical distance in Fig. 4. From an over all perspective, we can see that the performances of all systems degrade as the vertical distance increases. Although the average outage probability of the single-hope and DF systems are very close to each other, the former performs better than the latter when the vertical distance is small (i.e. distance less than 2.4 m), and the performance of the DF is dominant over the single-hop performance for greater distances. On the other hand, the SDF/IDF systems have smaller outage probability compared to outage probabilities of both single-hop and DF systems.

The average outage probability of the systems is drawn as a function of the maximum cell radius of the LED in Fig. 5. This is to illustrate the influence of the maximum cell radius of the LOS of the LED on the system performance. Likewise the previous figures, it can be noticeable that, the SDF/IDF systems have better performance than the other two proposed systems. As it can be seen from the figure, the single-hop and the DF systems have almost the same outage probability when the maximum cell radius of the LED is less than 3 m, from above 3 m the Df system outperforms the single-hop one. However, the maximum cell radius of the LED has a negative impact on the performance of all systems under consideration.

4.2. Energy-per-bit performance

The objective of this subsection is to investigate the energy-per-bit performance of the proposed systems. From an over all perspective of Figs. 6–8, we can see that the VLC system which is supported by IDF relaying protocol is the most energy efficient system compared to other proposed SDF and DF-based systems. This is simply because of the IDF relay will not cooperate unless requested to do so by the destination node. However, the single-hop system has almost the worst energy performance particularly for longer distances and higher values of the maximum cell radius. It is also seen that as the energy performance decreases for any increase of the vertical distance or the maximum cell radius for all relaying protocols and single-hop systems.

By having a closer look at Fig. 6, where the energy consumption is plotted as a function of outage probability and the vertical distance is 4.5 m, it is noticeable that the single-hop scenario consumes less energy than SDF scheme when the outage probability is less than 0.1. It is also shown that the DF relaying protocol represents the worst case energy consumption scenario when the end-to-end outage probability is equal to 0.38 and less, where the single-hop approach is the most in energy inefficient when the outage probability is more than 0.38 and vertical distance is 4.5 m. The IDF approach has less energy-per-bit consumption for all outage probability values compared to the other schemes. However, it can be seen that the higher the outage probability is, the lower is the energy consumption.

Fig. 7 illustrates the impact of the vertical distance to the user plane on the energy consumption of the proposed systems. It appears from this figure that both IDF and SDF schemes perform close to each other particularly at shorter vertical distances, whereas the energy performance of both systems is higher than the one achieved by DF system for the given distance values. It is also clear that the single-hop system is the most efficient system when the distance is less than 2.75 m and surpasses the DF approach when the vertical distance is 4.5 m and less. The previous statement indicates that the implementation of DF relaying protocol with VLC systems can be energy-inefficient if the vertical distance to user plane is relatively small.

The energy consumption is plotted with respect to the maximum cell radius of the LOS of the LED in Fig. 8. It is obvious that the energy consumption of all of the proposed systems increases when the maximum cell radius of the LED becomes greater. This clear Likewise the previous discussions, the IDF scheme is the most energy efficient approach compared to the other considered systems followed by the SDF relaying protocol. Although the vertical distance is kept at 4.5 m, the single-hop system is worst than DF relaying protocol in terms of energy consumption. This is because of the outage probability is 0.4 and the maximum cell radius of the LED changes from 2.9 m- to −3.4 m.

5. Conclusions

In this paper, we have introduced the idea of using different relaying protocols with the VLC system. The performance of the proposed systems was investigated in terms of outage probability and energy-per-bit. The main contribution of this paper is the derivation of the analytical expressions of the overall outage probabilities of the systems and the energy/bit consumption. The analytical results were validated by Monte Carlo simulations. The results showed that the performance of the proposed system declines when the vertical distance or the maximum cell radius of the LED increases. The results also indicated that IDF relaying protocol provides the best outage probability and energy-per-bit performance compared to the other proposed systems. This because of this relaying approach only takes part in the communication process if it is requested by the destination modem to cooperate. Furthermore, the single-hop approach outperforms the DF relaying protocol in terms of outage probability and energy-per-bit performance when the vertical distance is relatively small.

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